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Analysis and Design of Quasi–Optical Filters

Maurizio Bozzi and Luca Perregrini

Abstract – This paper presents an optimisation procedure for the automatic design of frequency selective surfaces. The optimisation tool is based on the genetic algorithm, and embeds an analysis method we recently developed. The implementation of the optimisation code and its application are described, and the major advantages of the method are discussed. An example is also reported, where the code is applied to the optimisation of frequency selective surfaces with circular holes.

Fig. 1: A thick metal screen perforated periodically with arbitrarily shaped apertures.

I. INTRODUCTION

Metal screens perforated periodically with apertures are used as *Frequency Selective Surfaces* (FSSs) from the microwave to the infrared region [1,2]. Their design requires both a fast and flexible analysis code and an efficient optimisation tool, especially when tight electrical constrains are imposed.

Recently, we presented a novel algorithm for the analysis of FSSs, consisting of a thin [3] or thick [4] metal screen perforated periodically with arbitrarily shaped apertures (Fig. 1). This algorithm is based on the Method of Moments (MoM) and on the Boundary Integral–Resonant Mode Expansion (BI–RME) method [5], and has been implemented in a computer code. This code was widely applied to the analysis of FSSs both in the microwave [6] and in the THz region [7], showing its efficiency, flexibility and reliability. These capabilities make possible its use within a procedure aiming at the automatic design of FSSs.

The optimisation procedure requires the minimisation of a properly defined *cost function*, which represents the distance between the actual and the desired behaviour of the FSS. The minimisation of the cost function can be reached via either local or global search methods. The local search methods (*i.e.*, gradient descend methods) are usually very fast if the starting point is close to the final solution. However, they run the risk to be trapped in a local minimum, especially when the cost function is particularly uneven. On the contrary, the global search methods (*e.g.*, the evolutionary approaches) are able to investigate the whole space of the possible solutions, avoiding the local minimum problem. For this reason, we implemented an optimisation tool, based on the Genetic Algorithm (GA), intended for the automatic design of FSSs.

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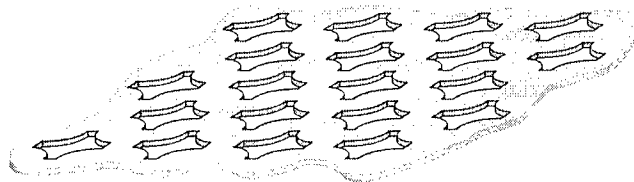e–mail: m.bozzi@ele.unipv.it, l.perregrini@ele.unipv.it

In this paper, we briefly discuss the analysis algorithm and the optimisation procedure, and present the preliminary results in the optimisation of FSSs with circular holes. The investigation of this simple structure permits to better understand the capabilities of the GA, highlighting advantages and drawbacks intrinsic of this approach. Some final remarks indicate a possible improvement of the optimisation procedure that will permit to overcome the drawbacks, while keeping all the advantages of the GA approach.

II. MoM/BI–RME ANALYSIS OF FSSs

When considering FSSs whose overall dimensions are larger than the cross–section of the impinging electromagnetic wave (as usually happen when considering a focused beam), the analysis of the FSS can be carried out under the infinite array approximation. In fact, in that case, the contribution to the scattered wave due to the diffraction at the edges of the FSS is negligible. Under this hypothesis, and representing the impinging wave as a uniform plane wave, by using the Floquet theorem the study of the FSS reduces to the investigation of a single unit cell with periodic boundary conditions (Fig 2).
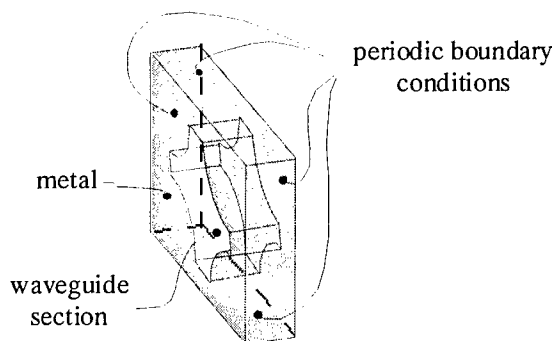

Fig. 2: Unit cell of the periodic structure of Fig. 1

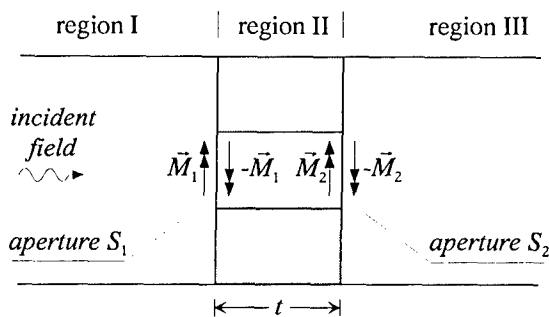region I | region II | region III

Fig. 3: Side view of the unit cell after the application of the equivalence theorem.

The analysis of the unit cell is based on the application of the equivalence theorem: the terminal cross–section of the waveguide section shown in Fig. 2 are closed by perfect metal sheets, and unknown magnetic current densities are considered over them to guarantee the continuity of the electric and magnetic fields across the apertures S_1 and S_2 (Fig. 3).

Thus, the fields in free–space (region I and III) are expressed as a combination of Floquet modes, whereas the fields in the waveguide (region II) are represented as a combination of the modal fields of the waveguide.

By enforcing the continuity of the tangential components of the electric and magnetic fields on S_1 and S_2, two coupled integral equation are obtained, which are solved by the MoM (see [3,4], for more details).

The use of the MoM requires the choice of a suited set of basis and test functions to represent the (unknown) magnetic current and to test the integral equations. The choice of the basis functions greatly affect the accuracy, flexibility and efficiency of the method. The better choice is to consider entire domain basis functions, i.e., functions that span the entire domain where the unknown quantities are defined and satisfy the proper boundary conditions. In our problem these functions are the electric modal fields of the waveguide shown in Fig. 2. In the past, entire domain basis functions were used only for circular or rectangular holes, since in these cases they are known analytically [1].

We extended the use of entire domain basis functions to the case of arbitrarily shaped aperture, exploiting the capabilities of the BI–RME method [5]. This method is very fast and flexible, and allows for calculating a large number of modes of an arbitrarily shaped waveguide in a few seconds.

Furthermore, the BI–RME method yields as a primary result the boundary values of the potentials of the TE and

TM waveguide modes. These results can be used for a direct calculation of the integrals involved in the MoM matrices, by reducing surface to line integrals [3,4].

The possibility of considering arbitrarily shaped apertures adds degree of freedom in tailoring the frequency response of the FSS, and, moreover, it allows for taking into account the unavoidable inaccuracies due to the fabrication process, e.g. rounding of edges or corners in the aperture shape [7].

III. EVOLUTIONARY OPTIMIZATION OF FSSs

Optimisation tools based on the Genetic Algorithm (GA) received particular attention in the last years [8,9,10,11].

The major advantage of the evolutionary approach with respect to standard optimisation tools (e.g., gradient descent methods, Quasi–Newton methods) is the robustness: in fact, the evolutionary methods explore the whole space of solutions, with no risk of being trapped in a local minimum. Moreover, no initial guess or tentative solution is required to the user.

The basic idea of the evolutionary optimisation originates from the human genetics: the geometrical data of the FSS are coded as the genes of a chromosome (Fig. 4). Firstly, a population of chromosomes is randomly generated. A fitness value is calculated for each element of the population. The value of this parameter indicates how well the performance of the corresponding FSS satisfies the optimisation target. The target consists of a list of required transmission or reflection coefficient in a number of frequency points. The fitness depends on the Euclidean distance between the required and the achieved performance: the higher the fitness, the closer to the target. Then, new generations of the population are created, through the mechanisms of selection, cross–over and mutation [12]. Chromosomes are selected on the basis of favouring individuals with higher fitness, which reflects how well the individual fits the environment. After a number of generations, the best fitting chromosome is taken as the optimal solution of the problem.

Besides the optimal solution, the algorithm provides a population of chromosomes, which are quasi–optimal solutions. In fact, some of these chromosomes present a fitness slightly worse than the optimal one. Nevertheless, these solutions could be interesting from a mechanical or technological point of view, if they either guarantee better mechanical features (e.g., stiffness) or are easier to fabricate.

We implemented a genetic optimisation routine, based on the GA library PGA–Pack [13]. This optimisation routine embeds our analysis code based on the BI–RME method. Even if the analysis code permits to manage with FSSs comprising arbitrarily shaped apertures, we preliminary limited the optimisation code to FSSs with circular holes. In this case, in fact, only five geometrical quantities are needed to characterise the FSS (Fig. 4a), and the check for the physical consistence of the structure is trivial. This allowed us for deeply investigating the effect of the GA parameters on the optimisation process. We decided to use chromosomes with five real genes (Fig. 4b), which are selected by a binary tournament or probabilistic tournament selection and combined through uniform cross–over; furthermore, a mutation rate ranging from 1% to 5% is applied.
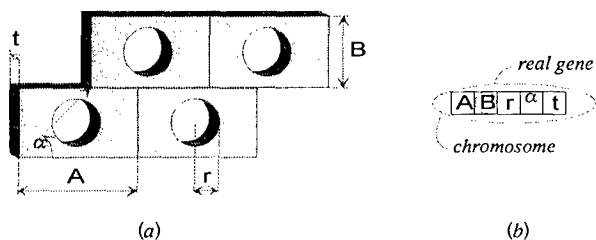
Fig. 4: Structure of a FSS with circular holes (a) and the corresponding chromosome (b).
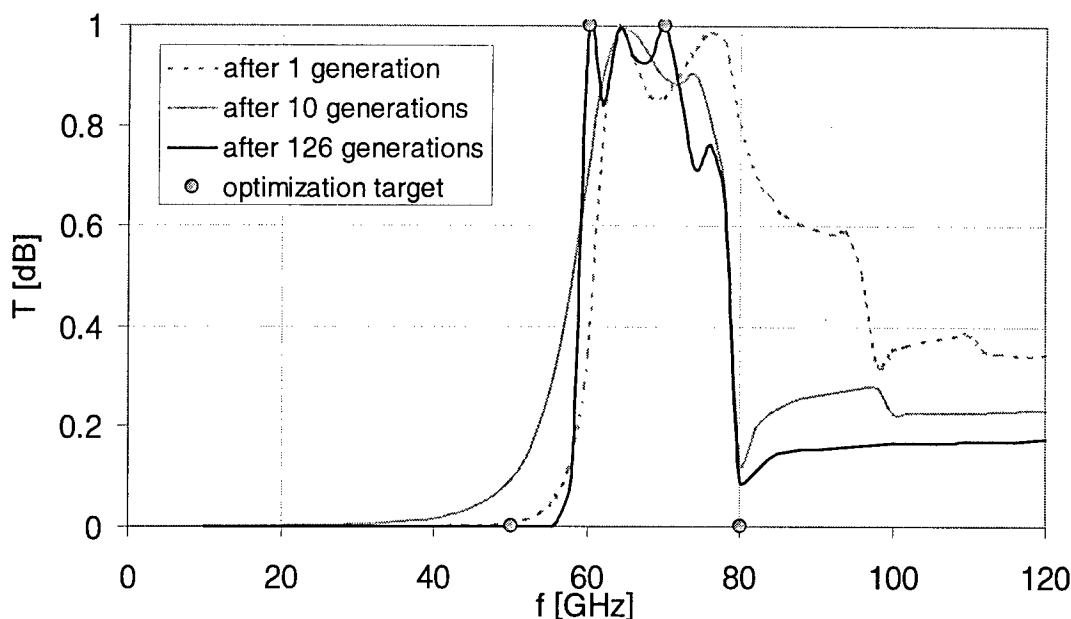
Fig. 5: Power transmittance of the FSS with circular holes vs. operation frequency (TM mode, normal incidence): best solution after 1, 10, and 126 generations.

IV. PRELIMINARY RESULTS

The example we present refers to the optimisation of an FSS with circular holes (Fig. 4a). This structure has been widely investigated for applications in the THz region [7,14], and empirical formulas for its design has been derived. Therefore, the choice of this test structure permits to gain an insight into the behaviour of the GA.

The optimisation targets are imposed in four frequency points: total reflection of the TM mode at 50 and 80 GHz, total transmission of the TM mode at 60 and 70 GHz (see the dots in Fig. 5). Normal incidence is considered.

The population size was fixed at 250 chromosomes. At each generation, 40 chromosomes were discarded and replaced by using probabilistic tournament selection, cross–over and 5% mutation rate.

Fig. 5 shows the frequency response of the FSS corresponding to the best chromosome of the population after 1, 10, and 126 generations. After 126 generation all the targets were practically satisfied, and no further significant improvement was observed.

To deeply understand the behaviour of the GA, we reported in Fig. 6 the historical evolution of the optimisation parameters (genes), as well as of the distance to target. It can be observed that some parameters (e.g., the radius R of the holes and the thickness t) converge rapidly to the final value. This fact is not surprising since these parameters determine the resonant frequency of the filter (the radius) and the slope of the transmission parameter (the thickness) [14].

The GA method always converges to the required solution, but, however, the rate of convergence becomes slow when approaching the target. This is an intrinsic drawback of the GA approach. In fact, at the beginning of the procedure, the mutation permits to rapidly investigate the space of the possible solutions, locating a set of solutions near to the target. On the contrary, the algorithm is not clever enough to rapidly refine these solutions. For this reason, a better approach could consist in coupling the GA optimisation procedure with a local search minimisation method. We implemented this hybrid approach for the analysis of non–linear circuits [15], obtaining, in some case, a dramatic improvement of the efficiency of the code. This hybrid optimisation approach uses the GA for finding a reasonable initial guess and then a gradient based method for its refinement. With this approach we will keep unchanged the flexibility and reliability of the optimisation code (no initial guess required, convergence guarantee), while improving its efficiency.

V. CONCLUSION

In this paper, we presented the implementation of a GA optimisation code for FSSs. The code was preliminarily applied to the optimisation of metal screens perforated periodically with circular holes, with the aim of fully investigating the GA parameters. Although this tool allows for the automatic optimisation of FSS, without any need for human intervention or initial guess, the convergence rate becomes slow when approaching the target. For this reason, a better approach could be the coupling of the GA with a local search optimisation method. This hybrid optimisation approach, starting with the GA for finding a reasonable initial guess and then inserting a gradient based method, could strongly reduce the computing time.
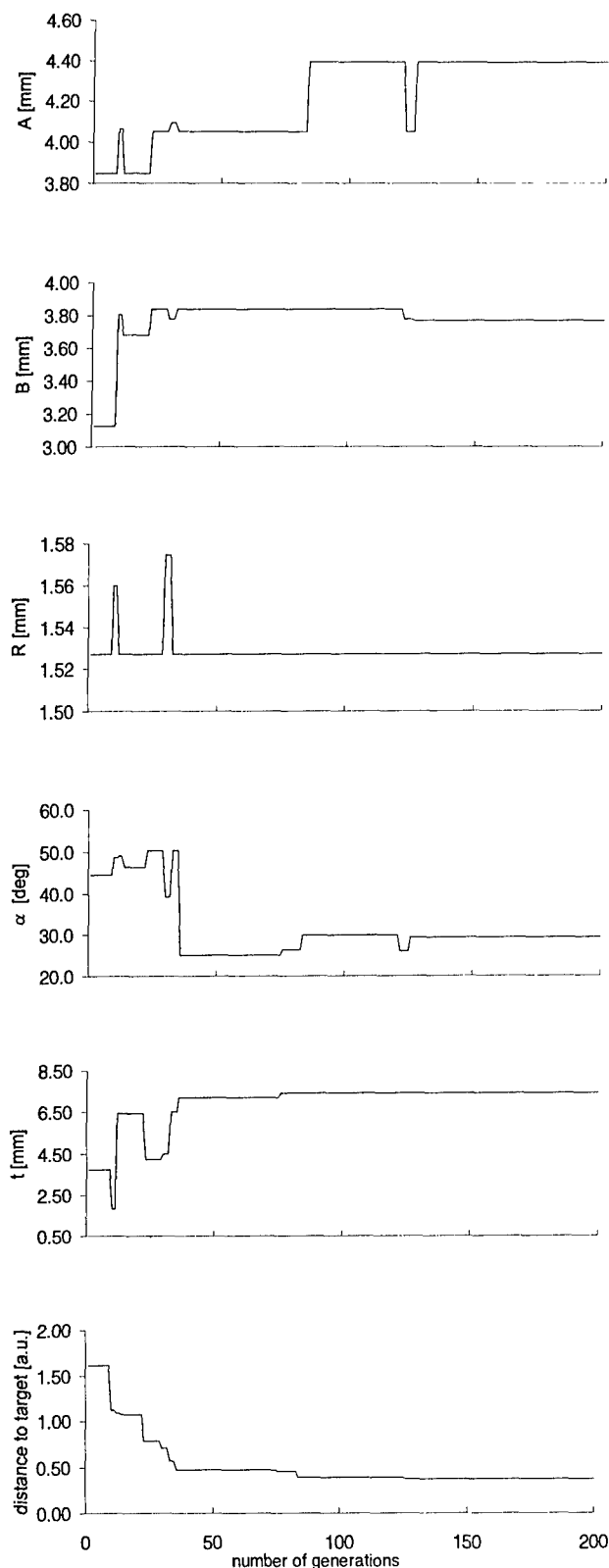
VI. ACKNOWLEDGEMENT

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Fig. 6: Historical evolution of geometrical quantities (genes) and distance to target during the optimisation of FSS with circular holes.

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